

STUDY ON PREVENTION OF REBAR CORROSION THROUGH CATHODIC PROTECTION BY USING SACRIFICIAL ANODE

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ABSTRACT

This study investigated the performance of sacrificial anode system to provide cathodic protection against rebar corrosion to chloride-contaminated RC structures. Reinforced concrete beams, with a single 12mm-Ø bar, were exposed to 5% sodium chloride solution, and corrosion rate was accelerated by the application of external current. Corrosion initiation was monitored by Cu/CuSO₄ half-cell potential and corrosion rate was measured by galvanic current measurement. At about 8% corrosion of rebar, a sacrificial anode cathodic protection (SACP) system was attached to the corrosion cell under a constant external current supply. It was found that SACP could successfully divert the corrosion current from the main rebar, accounted up to maximum 91.6% of the total corrosion current.

Keywords: Corrosion, half-cell potential, corrosion rate, SACP

1. INTRODUCTION

Corrosion of reinforcing steel is one of the most important and prevalent mechanism of deterioration for concrete structures in marine environments. High permeability of concrete, poor design detailing and construction defects are the problems which allow the ingress of salt and moisture into concrete. The higher concentration of salt and moisture can result in accelerated corrosion of reinforcing steel. Conventional repair methods, which include the removal and replacement of damaged concrete have been proved to be ineffective unless the progressive corrosion potential is hindered.

Over the last few years, Cathodic Protection (CP) has increasingly been used all over the world to provide long term corrosion control for reinforced concrete structures, especially the highway structures and bridges. CP is an electrochemical method which can effectively stop further corrosion of the reinforcing steel regardless of the salt content in the concrete. This is aimed to study the mechanism of corrosion prevention by using sacrificial anode and to develop the same from locally available technology and evaluate its capacity towards corrosion prevention.

Cathodic protection (CP) has been widely used to control corrosion in numerous industrial processes (e.g., pipelines, offshore structures, ships, etc.), but it was not until the 1970s that CP was introduced as a protective system for reinforced concrete infrastructure. Subsequently, its application has increased steadily and it is now considered the only system capable of stopping corrosion even at high chloride concentrations or when deterioration is at an advanced state (Stratfull 1988).

Two methods are commonly used for implementing cathodic protection. These are known as (1) impressed current systems (not discussed in this investigation) and (2) galvanically coupled systems (Stratfull 1988). Galvanically coupled systems, also referred to as sacrificial anode cathodic protection (SACP) systems, do not require external power to supply electrons to stop corrosion, but instead utilize the inherent difference in the electrical potential of dissimilar metals. As an example, if zinc (typical potential of -1,100 mV versus copper-sulfate electrode, CSE) were to be electrically connected to regular corroding steel (typical potential of -400 mV versus CSE in intermediate internal humidity concrete, and -650 mV versus CSE in wet concrete), it would result in zinc giving out electrons (referred to as an anode) to the steel (referred to as the cathode). This is the same principle at work in a battery.

Some recently developed SACP systems use anodes that are attached to the reinforcing steel as a circuit element which can divert the corrosion current of rebar. The materials commonly used for preparing sacrificial anode are zinc (Zn), aluminium (Al), and magnesium (Mg).

2. METHODOLOGY

This section describes the experimental program that was used to evaluate the effectiveness of the sacrificial anode cathodic protection (SACP). The material properties and mix proportion of concrete are presented. The dimensions of specimens and the exposure condition are discussed in the following subsections.

2.1 Materials

Crushed brick aggregate with maximum size of 12mm (0.5”) was used as coarse aggregate. The bulk-specific gravity [saturated-surface-dry (SSD)] was 2.39, oven-dry bulk-specific gravity was 2.36, and the absorption capacity was 1.38% in accordance with ASTM C 127. The dry unit weight was 1594.6Kg/m³ (99:55 lb/ft³) in accordance with ASTM C 29.

Graded river sand was used as a fine aggregate with a fineness modulus equal to 1.64 in accordance with ASTM C 136. The bulk-specific gravity (SSD) was 2.66, oven-dry bulk-specific gravity was 2.62, and the absorption capacity was 1.05% in accordance with ASTM C 127.

Portland cement was used for all mixes described in this study. The cement-specific gravity was 3.2. The steel reinforcement used was Grade 500W deformed bar with diameter 12 mm (0.5 in.). Zinc was used as the sacrificial anode material which was covered by mortar [weight proportion 1(cement):3(FA)] to prepare a SACP system. Chemical composition of zinc is presented in Table 2.

Table 2: Chemical Composition of the zinc

Chemical compound	Weight percent
Zinc	99.8-99.9
Impurities	0.1-0.2

2.2 Description of Specimen

Concrete specimens used in the present investigation are illustrated in Figure 1. The beam shown in Figure 1(a) having dimensions 100 mm wide by 100 mm high by 1000 mm long, was reinforced with a single standard 12 mm diameter 500W reinforcing steel bar and the cylinder shown in Figure 1(b) was 100 mm in diameter and 200 mm in height. So the exposed area of steel to corrode is 37680 mm² (261.7in²) in beam and 7536 mm² (12.56 in²). The cover of the reinforcing steel was 50 mm in both side. To avoid excessive corrosion at the ends of reinforcing bar, the ending 60 mm range of the bar in the beam was coated with epoxy.

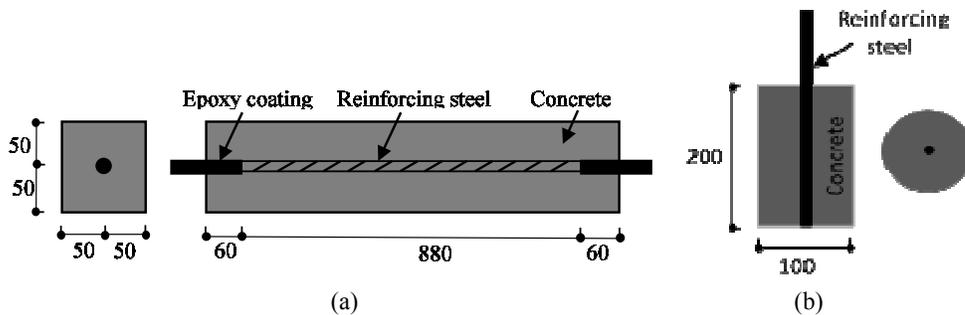


Figure 1: Specimen Geometry (mm)

A normal weight concrete (with a water-cement ratio [w/c] of 0.5) was used in this investigation. The weight proportions of the concrete mixture were 1(cement):2(FA):4(CA):0.5(water). Specimen was cured for 28 days in a relative humidity (room) ranging from 50-60% at an average temperature of 28^oC before test setup. The 28-day compressive strength of the concrete (4”x8” cylinder) was approximately 18 MPa (2600 psi).

3. EXPERIMENTAL PROCEDURE

3.1 Half-cell Potential Measurement

The copper-copper sulphate (Cu-CuSO₄) half-cell electrode was selected for corrosion measurement in the present research. The testing procedure followed the standard test method for half-cell potentials of reinforcing steel in concrete, ASTM C 876. Potential readings were taken daily at three different locations that were equally distributed along a beam. According to ASTM C 876, if the Cu-CuSO₄ half-cell potential reading is more positive than -0.20V CSE (copper-copper sulphate electrode), there is a greater than 90% possibility that no corrosion is occurring in the area at the time of measurement. If the potential reading is in the range of -0.20 to -0.35V CSE, corrosion activity of the reinforcing steel is assumed to be uncertain. If the potential reading is more negative than -0.35V CSE, it is assumed that a greater than 90% probability of the reinforcing steel corrosion is occurring.

3.2 Galvanic Current Measurement

Galvanic current was also used to monitor the corrosion process of reinforcing steel in the present study. As shown in Figure 2 a copper plate was placed in the 5% Sodium Chloride (NaCl) solution and electrically connected to the reinforcing bar through shunt resistor (2.2 ohms). This type of corrosion cell composed of two dissimilar metals (copper and carbon steel) in contact and sharing a common electrolyte (concrete pore solution) is called a galvanic cell. Of the two dissimilar metals, the metal with more negative standard potential value serves as anode in the corrosion cell (such as carbon steel, $E = -0.65V$), while the noble metal with the less negative standard potential value serves as cathode (such as copper, $E = -0.36V$). The current that flows between the galvanic couple is called galvanic current, the amount of which can indicate the degree of corrosion activity in the cell. In the present study, the galvanic current was monitored daily for each beam through a resistor, as shown in Figure 2. The galvanic corrosion current I_j was calculated based on the measured voltage V across the shunt resistor R ; (that is $I_j = V/R$).

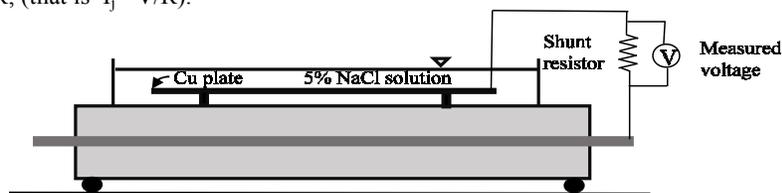


Figure 2: Test Set-Up for Galvanic Current Measurement

3.3 Application of External Current

After corrosion initiation, an external direct current was applied to some specimens through a rectifier to accelerate the corrosion propagation process. A beam was connected to the external DC current as shown in Figure 3. The rectifier had one end connected to the reinforcing steel in the specimen and the other connected to the copper plate via the shunt resistor. The voltage applied to the specimens was approximately 5.0V for the corrosion test.

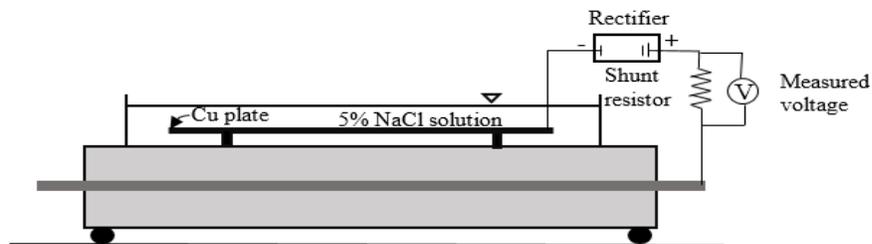


Figure 3: Test Set-Up for Application of External Current

The corrosion rate (defined as weight loss or percentage of weight loss of reinforcing steel in the present study) can be calculated based on the current passing through the shunt resistor according to ASTM G 102-89. This corrosion current was measured by a multi meter as shown in Figure 3. According to Faraday's law, the total weight loss of a reinforcing steel bar that is oxidized by the passage of electric charge can be expressed as follows

$$W = [TC] * \frac{EW}{F} = \left\{ \sum \frac{I_j + I_{j-1}}{2} * (t_j - t_{j-1}) \right\} * \frac{EW}{F} \quad 1$$

Where,

W = total weight loss of reinforcing steel, gm

TC = total electric charge (in amp-s or coulombs)

EW= equivalent weight, indicating the mass of metal in grams, that is oxidized.

For pure elements the EW is given by $EW=W/n$; where W is the atomic weight of the element, and n is the valence of the element. For carbon steel, the EW is approximately 28g and for zinc it is approximately 32.7g. F is the Faraday's constant in electric charge (F=96490 coulombs). I_j is the current in amps, at time t_j in seconds.

3.4 Measurement of Diverted Current through Sacrificial Anode

An SACP system stated before set up with the rebar which has shown in Figure 4. Since the SACP was setup in parallel with the rebar, the total current will be split and the amount of current passed through the SACP will be measured by an ammeter.

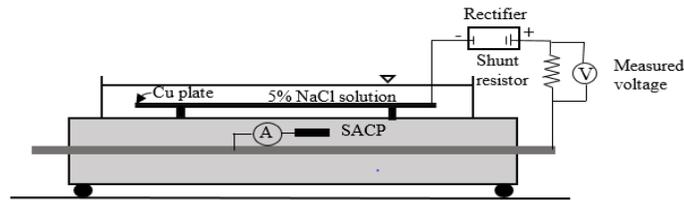


Figure 4: Test Set-up for Diversion of Current through Sacrificial Anode

4. RESULTS AND DISCUSSION

4.1 Corrosion Initiation

Figure 5 presents the half-cell potential measurements of concrete specimen ponding with 5% NaCl without any protection (B1) and with SACP system (B2). The potential measurements were taken periodically so that corrosion initiation could be monitored as a function of time. Each data point in the figure represents the average potential at three different locations of a beam. It can be observed that the specimen B1 without any protection had a potential, drop from -90 to -350 mV within approximately 69 h after ponding, which indicates that corrosion of reinforcing steel had most likely initiated in the specimen at approximately 3 days after starting of the corrosion test.

This phenomenon may be attributed to the high moisture content of specimen during the potential measurement, resulting in a low diffusion rate of oxygen through concrete matrix to the interface of steel and concrete. Therefore, free electrons accumulate at the interface, leading to the negative potential shift. Feliu et al. (2004) found that E_{corr} depends on the degree of wetness of the concrete to a great extent. The corrosion state of steel in chloride containing and chloride-free structures tends to be confused if the decision is based exclusively upon the E_{corr} values. Complementary methods are necessary regarding to this problem, such as the corrosion rate of the rebar and/or the resistivity of concrete at the moment the inspection is performed.

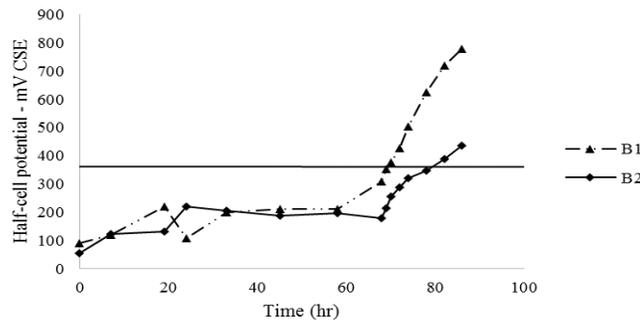


Figure 5: Effect of Sacrificial Anode on Corrosion Initiation

On the other hand, the specimen B2 having zinc protection showed a potential drop from -55 to -350 mV within 78 h after ponding in the same exposure conditions (ponding with 5% NaCl). It was indicative that the specimen having cathodic protection required a little longer time to initiate corrosion.

4.2 Concrete Resistivity

The electrical conduction in hardened concrete is an electrolytic process of ions flowing through the pore solution of cement matrix. The concrete resistivity may vary in very wide range with respect to the degree of moisture content. Lopez et al. stated that the resistivity of concrete can vary in the range of $5 \times 10^3 \Omega\text{-cm}$ – $5 \times 10^7 \Omega\text{-cm}$ when the saturated water ratio is in the range of 20–100%, due to the electrolyte supply. Using the standard method for electrical conductivity, ASTM C 1202-10, the electrical resistance of the concrete used in this investigation was 1102 $\Omega\text{-cm}$ under complete saturation condition. Jing Xu et al. (2009) had found that the electrical resistance of the concrete under the conditions of oven-dried, normal humidity and complete saturation for values of ρ were approximately 15 M $\Omega\text{ cm}$, 650 k $\Omega\text{ cm}$ and 20 k $\Omega\text{ cm}$, respectively.

4.3 Corrosion Propagation

A constant current of 5.0 V was supplied to accelerate the rate of corrosion to a great extent. The rate of corrosion is measured in terms of response voltage, which is measured across a shunt resistor (2.2 ohm). The half-cell potential is only a qualitative measure of corrosion whereas the response voltage presents the quantitative measure of corrosion. Different from half-cell potential measurement, galvanic current measurement directly measures the current flow in the galvanic couple and provides a quantitative indication of the degree of corrosion.

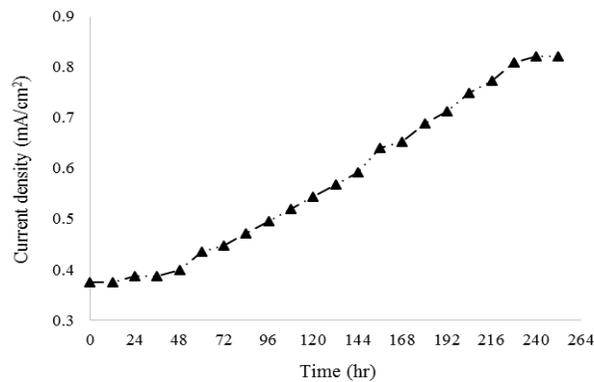


Figure 6: Variation of Current Density over time

Figure 6 demonstrates the relationship of corrosion current density with time. The current density i_{corr} is defined as the measured galvanic current I_{corr} normalized by the exposed area of the reinforcing steel A , or $i_{\text{corr}}(\mu\text{A}/\text{cm}^2) = I_{\text{corr}}/A$. According to Gonzalez et al. (1980) if corrosion current density is greater than $0.3 \mu\text{A}/\text{cm}^2$, reinforcing steel will be in an active state. S. Yoon et al. (2000) considered the threshold current density for active corrosion as $0.295 \mu\text{A}/\text{cm}^2$. It can be seen that corrosion current density at the time of application of external current was $0.37 \text{ mA}/\text{cm}^2$ which is far larger than the threshold value. Galvanic current depends on the electrical conductivity of concrete and it was stated earlier that the concrete, used in this study was a high conductive concrete. It can be seen from the Figure 6 that the current density firmly increased with the time. Which indicates that the current flow through the concrete with the increase in chloride penetration which is significantly increased due to formation of micro cracks.

The weight of metal corroded is calculated by the Faraday's law, which is a function of galvanic current ($W_{\text{loss}} \propto$ galvanic current). The rate and amount of corrosion was calculated according to ASTM G 102-89. By using the galvanic current the amount of metals corroded was evaluated, which can be illustrated in the Figure 7. It can be observed that, steel can be corroded by an amount of 62gm, which is approximately 8% of total weight, within 12 days.

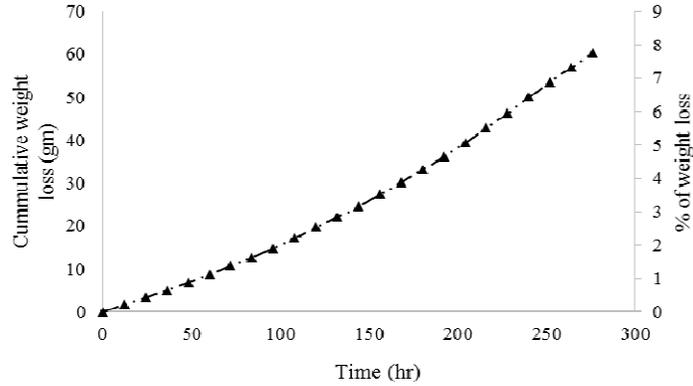


Figure 7: Corrosion Propagation of Rebar Due to External Current

Corrosion propagation of steel is linear up to a certain time and more obvious at the later stage. One explanation for this that after corrosion initiation, some microcracks in the concrete that were generated due to self-weight of concrete may be closed or become smaller and less connected by sealing with corrosion products and slowing down the chloride penetration (S. Yoon et al.). It was also proposed that a critical width below which the crack does not affect the corrosion process of reinforcing steel is approximately 0.1 to 0.3mm. Crack sealing may result in steel re-passivation and postpone corrosion propagation.

4.4 Corrosion Diversion

At about 8% corrosion of rebar, the SACP was inserted both into the beam and the cylinder connected with the rebar. The SACP, connected with rebar, complete the circuit with copper plate. An external current of 32.0V (DC) was maintained throughout the test. According to the principle of Cathodic Protection, due to the presence of comparatively more active metal (zinc), the reinforcing steel is forced to act as a cathode and the current will flow through the sacrificial anode (Zinc). But the total current in a parallel circuit will be distributed between the branches and total current will be the sum of current flow through the branches ($I=I_1+I_2$).

Current density of steel and sacrificial anode which is shown in Figure 8, illustrates that the current density of sacrificial anode is far greater than that of steel. It can be seen that a rapid decrease in current density of sacrificial anode is occurred but in the later stage it will remain constant (about 25 mA/cm²). On the other hand the current density of steel increases with time. Figure 8 shows that initially current density of sacrificial anode in cylinder was 45.8 mA/cm² and after 22 h it was remain constant (24.8 mA/cm²) which is approximately 91.6% of total corrosion current.

Figure 9 also shows the same pattern of current density through sacrificial anode. Initially the sacrificial anode divert the same current density to that of steel and the current density was 2.4 mA/cm². Figure also shows that the current density was reduced to 0.53 mA/cm² at about 72 h and it was remained constant. This pattern of current density may be explained as the product due to corrosion of sacrificial anode, make a film and reduced chloride penetration as well as the reaction.

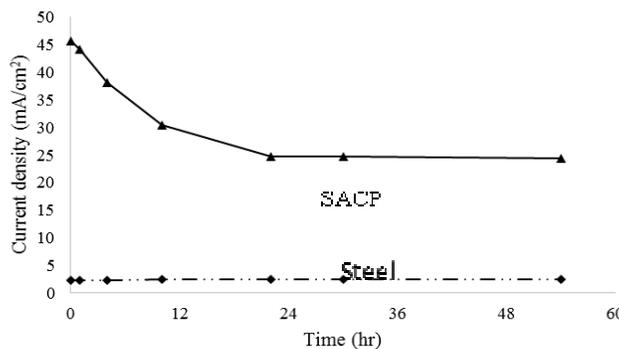


Figure 8: Relative Current Density of Steel and SACP in the cylinder

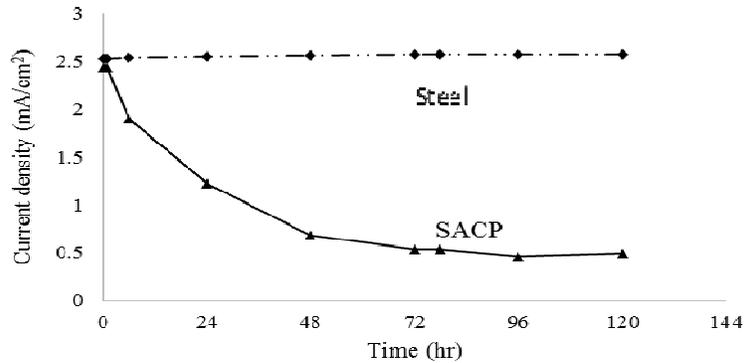


Figure 9: Relative Current Density of Steel and SACP in the Beam

5. CONCLUSIONS

This research illustrates that the effect of sacrificial anode on corrosion initiation and the preventive current density of sacrificial anode. Based on the present experimental results, the following conclusions can be drawn,

- The specimens, which were protected with sacrificial anode, take a little longer time to initiate corrosion.
- As the increase of corrosion rate, the corrosion current density increased gradually because of the propagation of microcracks.
- The sacrificial anode can successfully divert the corrosion current accounted up to 91.6% of total corrosion current. The current diversion rate effectively depends on the steel and sacrificial anode density in the concrete.

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